Search for New Physics with Two Photons and Large Missing Transverse Energy using CMS Detector at LHC

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Fermilab RA Talk

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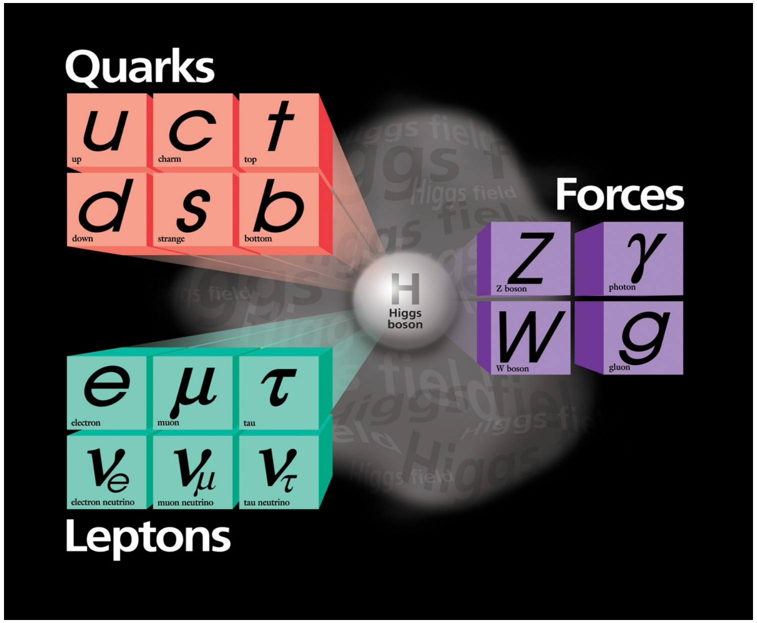
Motivations

- Standard Model describes particle physics well but that is not the whole story of our universe

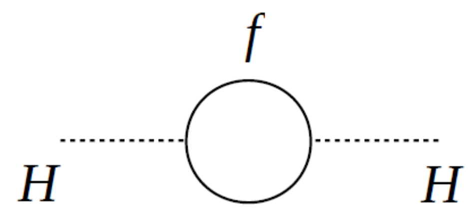


  - Higgs mass hierarchy problem
  - Gauge unification
  - Cosmological and astrophysical problem

Higgs Mass Hierarchy Problem

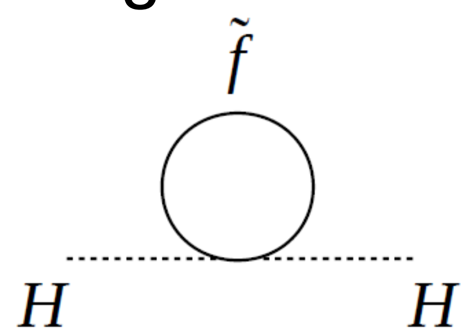
- Consider one-loop correction to Higgs mass due to Yukawa coupling
- If Λ is the order of the Plank scale, fine-tuning is needed to bring correction down to the order of $m_H^2 \sim (125GeV)^2$

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda^2 + \mathcal{O}(ln\Lambda)$$



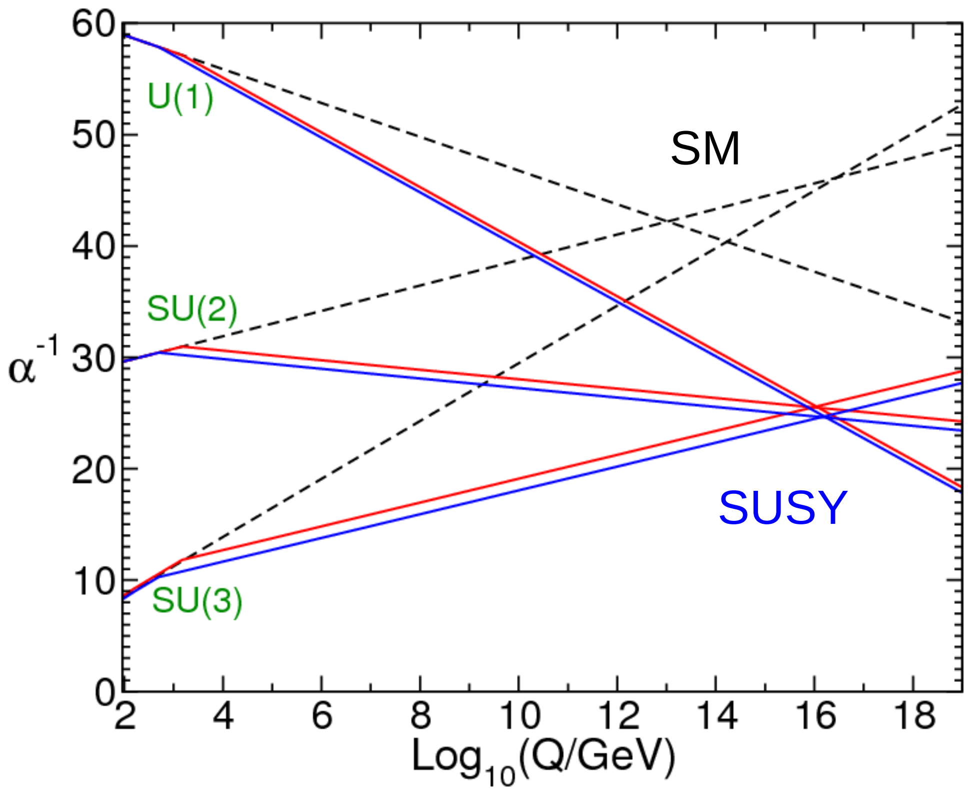
- Suppose we have a scalar partner which also contributes to one-loop correction
- Quadratic terms cancel, no fine-tuning is needed

$$\Delta m_H^2 = \frac{\lambda_{\tilde{f}}}{8\pi^2}\Lambda^2 + \mathcal{O}(ln\Lambda)$$

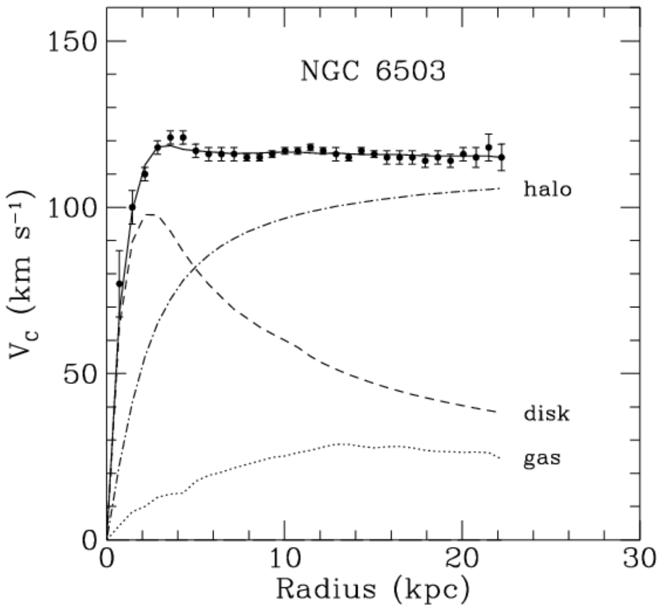


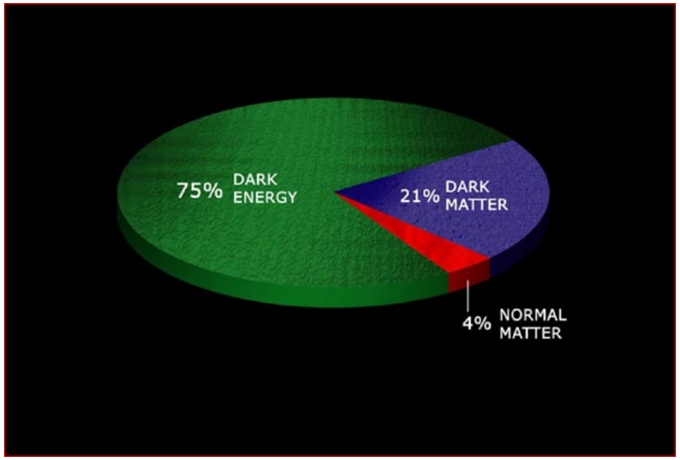
Gauge Unification

- Theoretically, one believes that $SU(3)_C \times SU(2)_L \times U(1)_Y$ is embedded in a larger group known as grand unification.
- Under the framework of Supersymmetry (SUSY), gauge couplings unify at high energy scale.



Dark Matter





- All cosmological observations indicate the existence of dark matter
- SUSY particles could be the candidate for dark matter

Supersymmetry

- Supersymmetry is a symmetry between fermions and bosons. $Q|Fermion\rangle = |Boson\rangle, \qquad Q|Boson\rangle = |Fermion\rangle$
- Equal fermionic and bosonic degrees of freedom requires each Standard Model particle and it's super-partner differ by spin with ½ unit.
- Commutation of SUSY operator and momentum operator implies the equal mass between Standard Model particle and it's super-partner
- Minimal Supersymmetry Standard Model (MSSM) is the minimal extension of the Standard Model
- No SUSY particle with the same mass as it's SM partner is observed meaning SUSY is a broken symmetry if SUSY exists.

SUSY-Breaking

Hidden Sector
SUSY is broken
at high energy scale

Messenger →

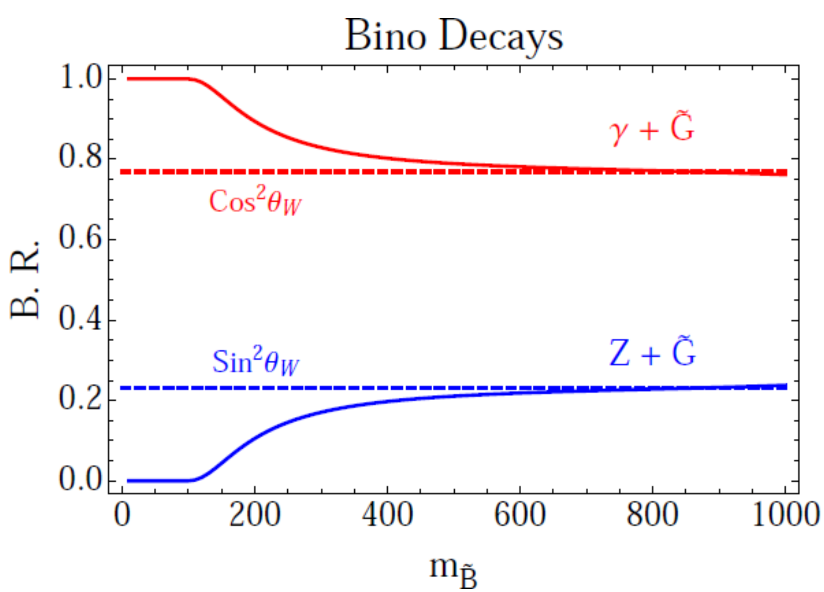
Visible Sector
contains MSSM

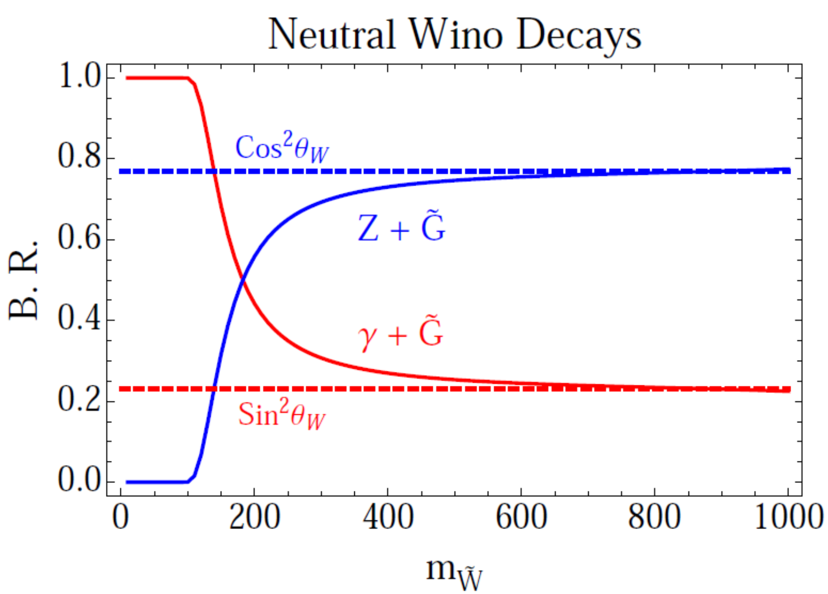
Messenger	SUSY breaking scale	Scale of messenger	Gravitino
gauge mediation	$\ll 10^{10}\,GeV$	$\ll M_{pl}$	$\ll 100\,GeV$
gravity mediation	$\sim 10^{10}\,GeV$	$\sim M_{pl}$	$\sim 100\,GeV$
anomaly mediation	$\sim 10^{12}\,GeV$	$\sim M_{pl}$	$\sim 10^{6}\,GeV$

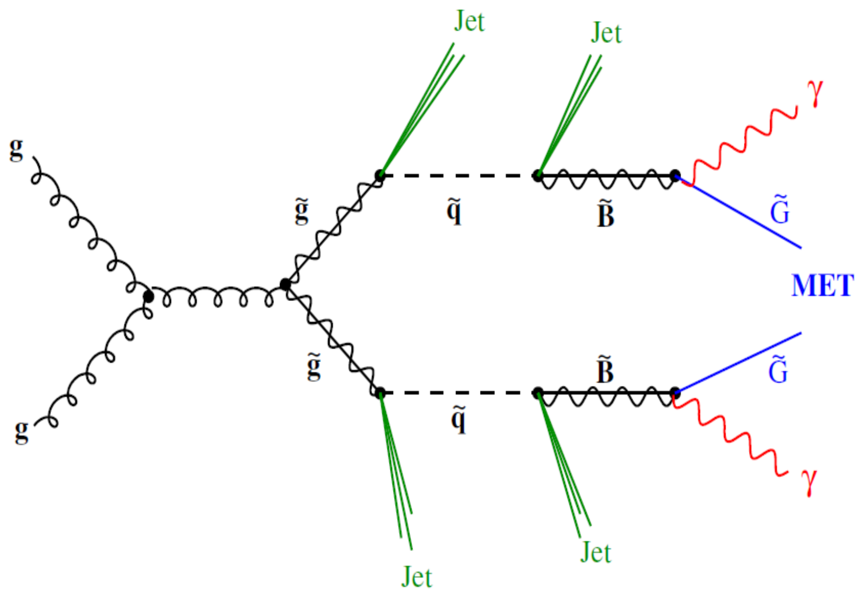
General Gauge Mediation (GGM)

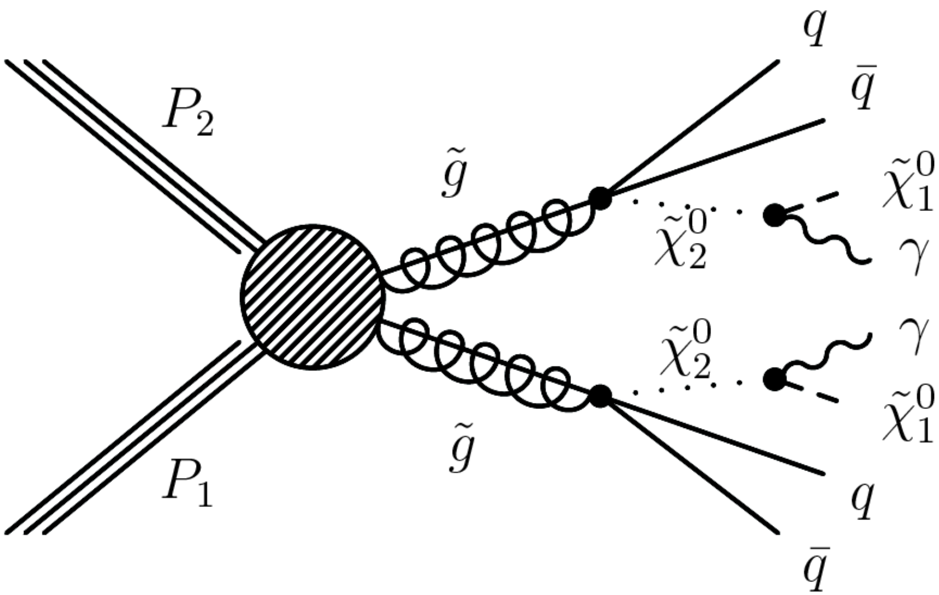
- Gravitino is the lightest SUSY particle (LSP) in GGM
- Consider Neutralino is the next-to-lightest SUSY particle (NLSP)
- Neutralino mass eigenstates are mixtures of Bino, Wino, and Higgsinos
- If R-parity is conserved, SUSY particles are produced in pair

$$R = (-1)^{3B+L+2s}$$

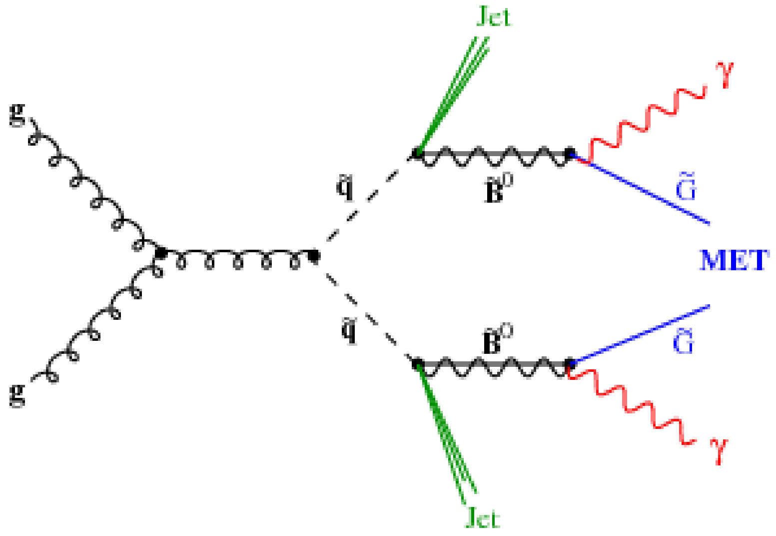




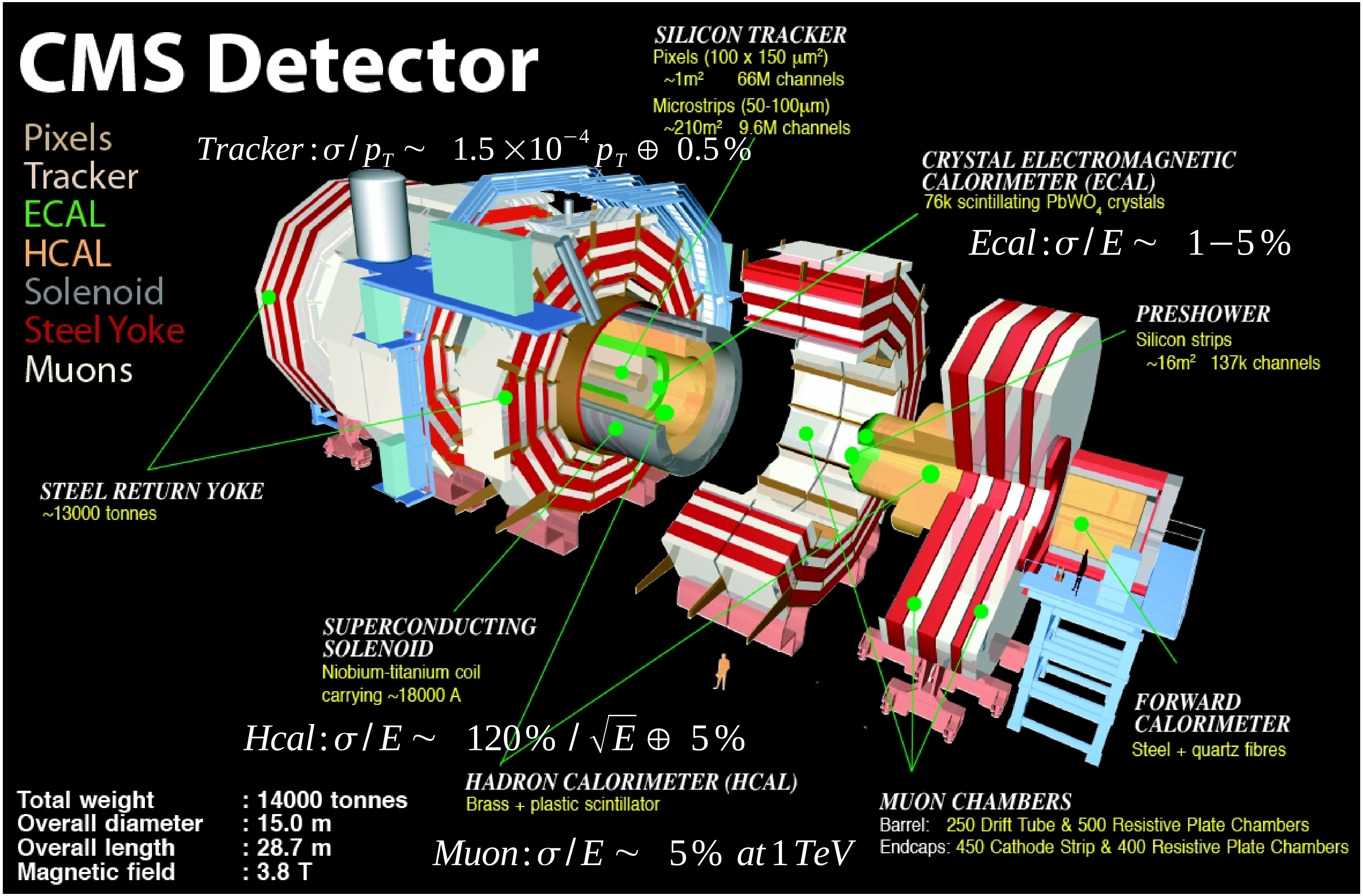




$\gamma\gamma$ Simplified Model



CMS Detector



Analysis Overview

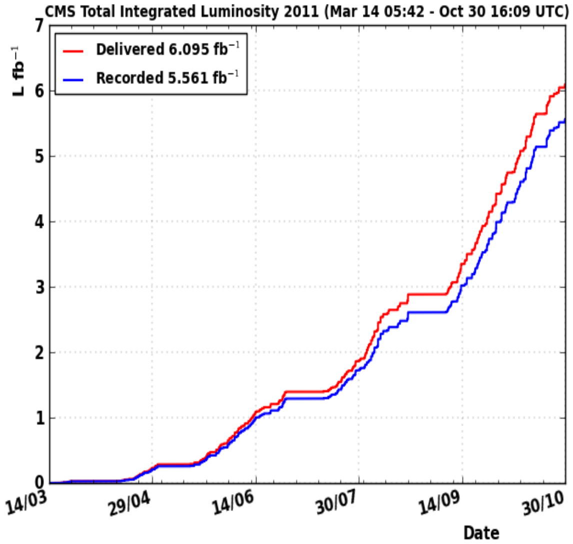
- Signal:
  - Events with two photons, at least one jet, and high missing transverse energy

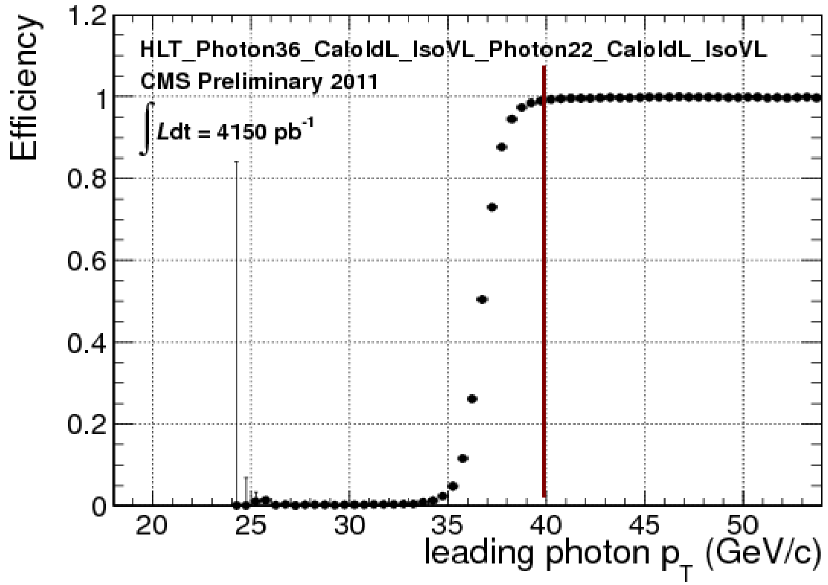
- QCD Background:
  - Main background of this analysis
  - Direct $\gamma\gamma$ production
  - $\gamma + jet$, or $multi\ jets$ while jet(s) fake photon(s)
  - No true MET events
  - Use control samples to estimate contributions

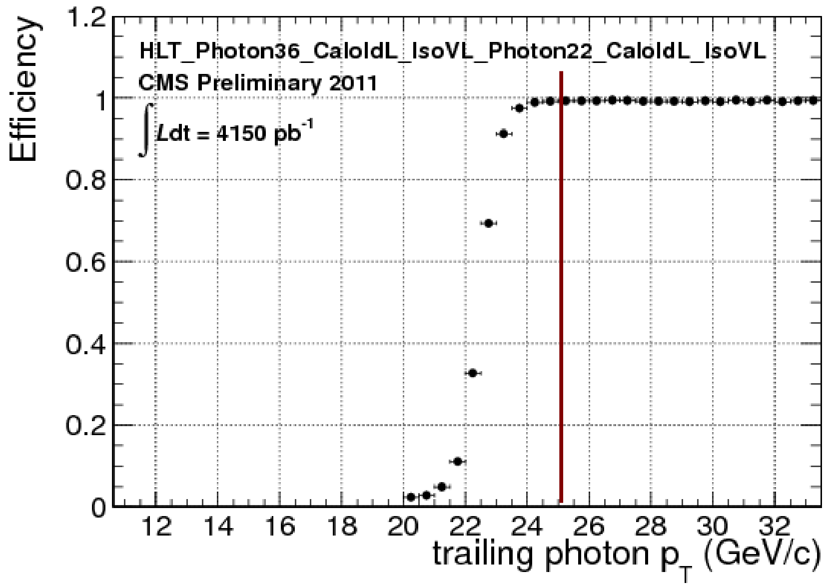
- ElectroWeak Background:
  - $W + \gamma \rightarrow e\,\nu + \gamma$
  - $W + jet \rightarrow e\,\nu + \gamma$
  - The electron is misidentified as a photon
  - Events with true MET
  - Apply electron mis-identification rate to control sample to obtain prediction

Dataset & Triggers

- $\sqrt{s}$ = 7 TeV proton-proton collisions data ~ 5 fb^{-1}
- HLT_Photon26_IsoVL_Photon18
- HLT_Photon36_CaloIdL_Photon22_CaloIdL
- HLT_Photon36_CaloIdL_IsoVL_Photon22_CaloIdL_IsoVL
- HLT_Photon36_CaloIdL_IsoVL_Photon22_R9Id
- HLT_Photon36_R9Id_Photon22_CaloIdL_IsoVL
- HLT_Photon36_R9Id_Photon22_R9Id







Identifications and Event Selections

Photons:

leading photon Et > 40 GeV
trailing photon Et > 25 GeV
$|\eta| < 1.44$

Electrons:

identical to photons' ID
but require PixelSeed
81 < M(ee) < 101 GeV

Fake Photons:

identical to photons' ID
but reverse combined Isolation
or $\sigma_{i\eta i\eta}$

Jets:

particle flow jets
Et > 30 GeV
$|\eta| < 2.6$

$\gamma\gamma$ Sample:

candidate sample

$e\gamma$ Sample:

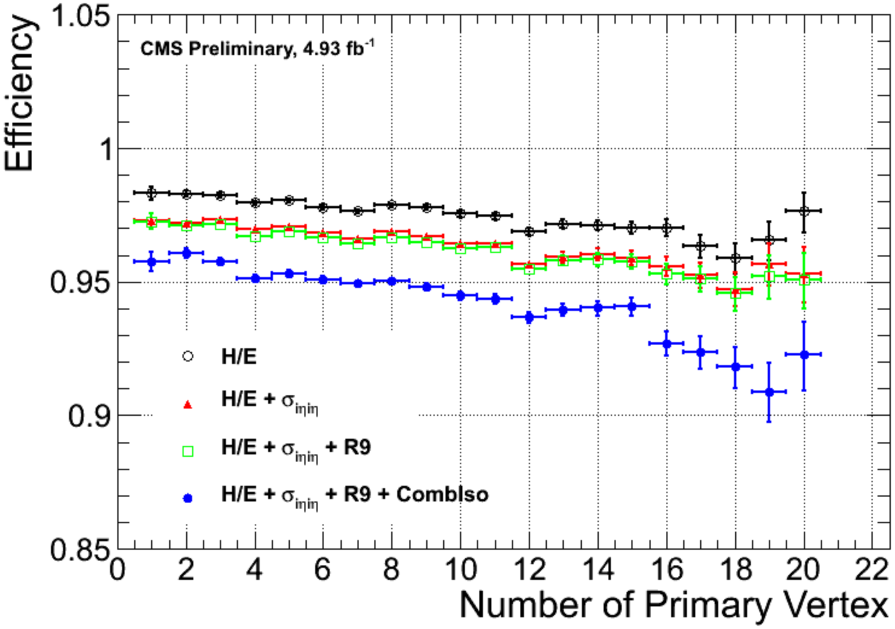
EWK background estimation

ff and ee samples:

QCD background estimation
control samples

Photon Id data/MC Scale Factor

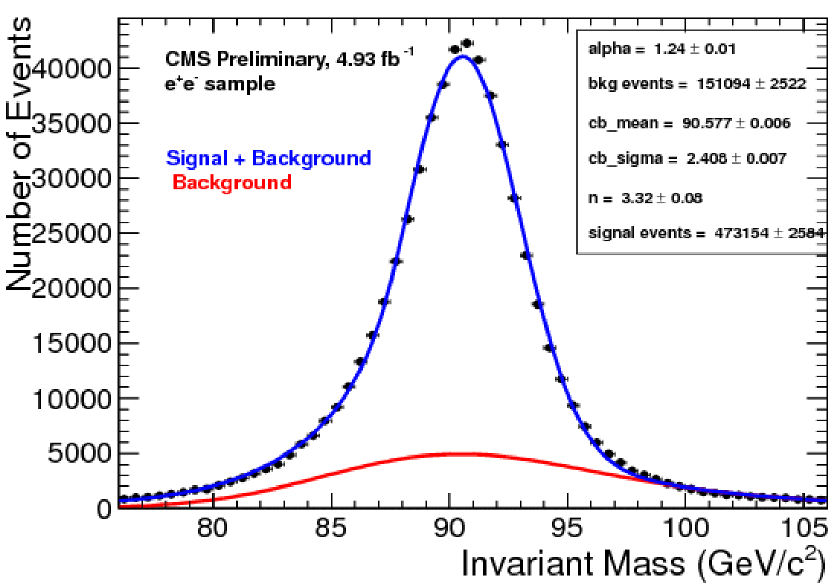
- Assume $\frac{\epsilon_{\gamma}^{data}}{\epsilon_{\gamma}^{MC}} = \frac{\epsilon_{e}^{data}}{\epsilon_{e}^{MC}}$
- Use tag and probe method to obtain ϵ_{e}^{data}
- A tag in $e^{+}e^{-}$ events must pass strict electron criteria while loose cuts are applied on a probe
- All tag-probe pair and pair whose probe passes photon id are fitted simultaneously

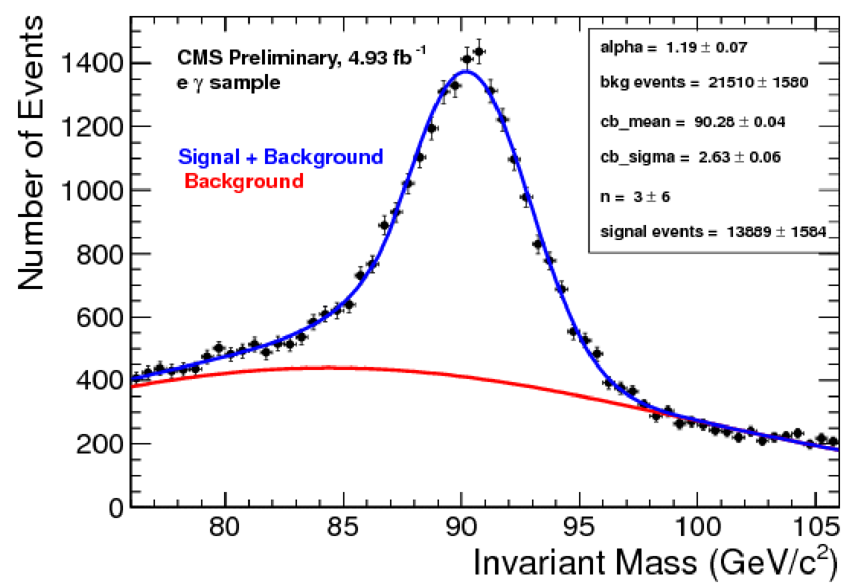


$$\frac{\epsilon_{\gamma}^{data}}{\epsilon_{\gamma}^{MC}} = \frac{\epsilon_{e}^{data}}{\epsilon_{e}^{MC}} = 0.994 \pm 0.002(stat.) \pm 0.035(syst.)$$

Estimation of MET Background (Electroweak)

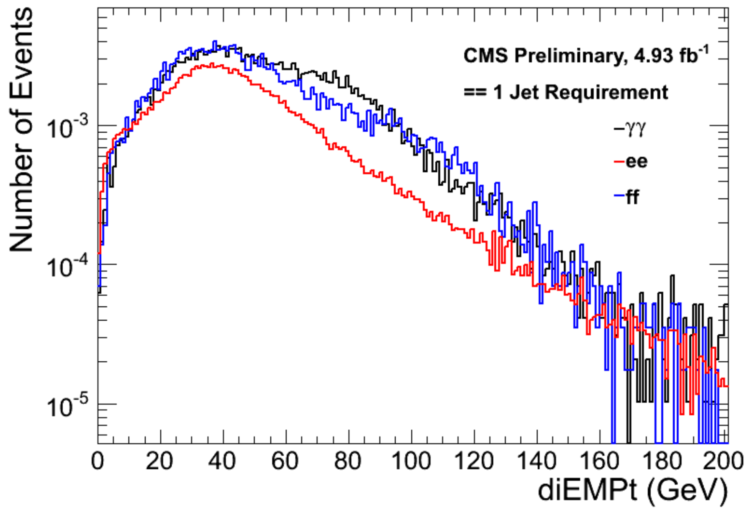
- Fit Z peak in ee and $e\gamma$ invariant mass spectra to get the numbers of events, respectively.
- $\dfrac{N_{e\gamma}(Z\rightarrow ee)}{N_{ee}(Z\rightarrow ee)} = \dfrac{2f_{e\rightarrow\gamma}}{(1-f_{e\rightarrow\gamma})}$ $\quad f_{e\rightarrow\gamma}$: $0.014 \;+/-\; 0.002(stat.) \;+/-\; 0.005(syst.)$
- Scale the MET distribution of $e\gamma$ sample by $\dfrac{f_{e\rightarrow\gamma}}{(1-f_{e\rightarrow\gamma})}$

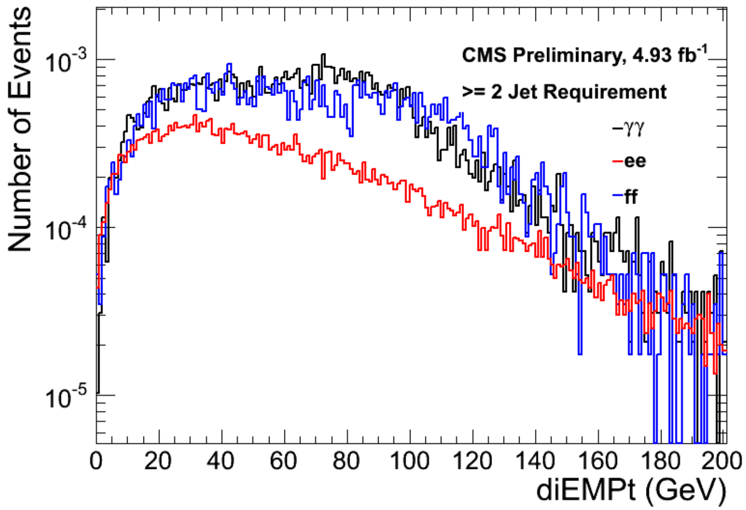




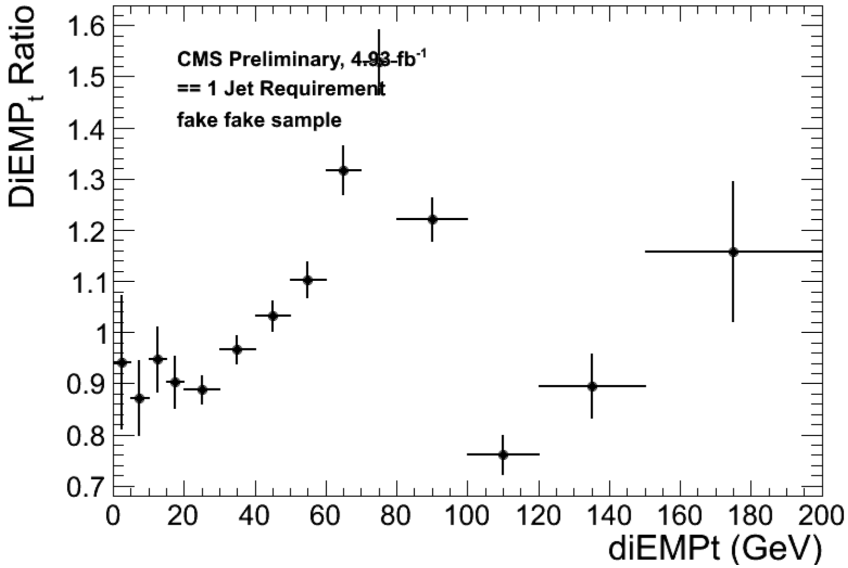
Estimation of MET Background (QCD)

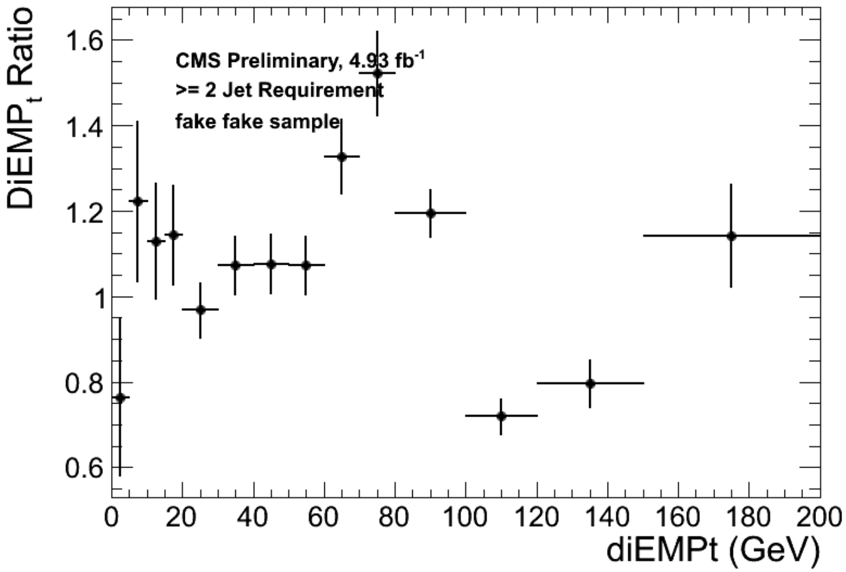
- Use both control samples (ff, ee) to estimate QCD MET distribution.
- If there is no TRUE MET in the event, the resolution of hadronic activity in the event will dominate the MET in the event.
- Take the di-EM Pt spectrum from candidate sample as a measure of hadronic activity in the event.
- Reweight the shape of MET distribution of control samples by using the di-EM Pt ratio of candidate sample and control samples.
- Normalize the reweighted MET distribution to low MET region (below 20 GeV) of candidate events.

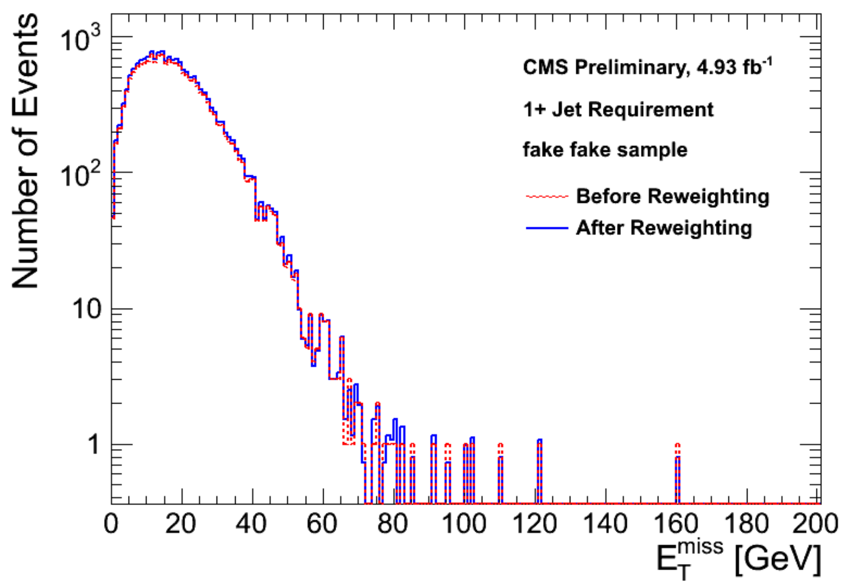




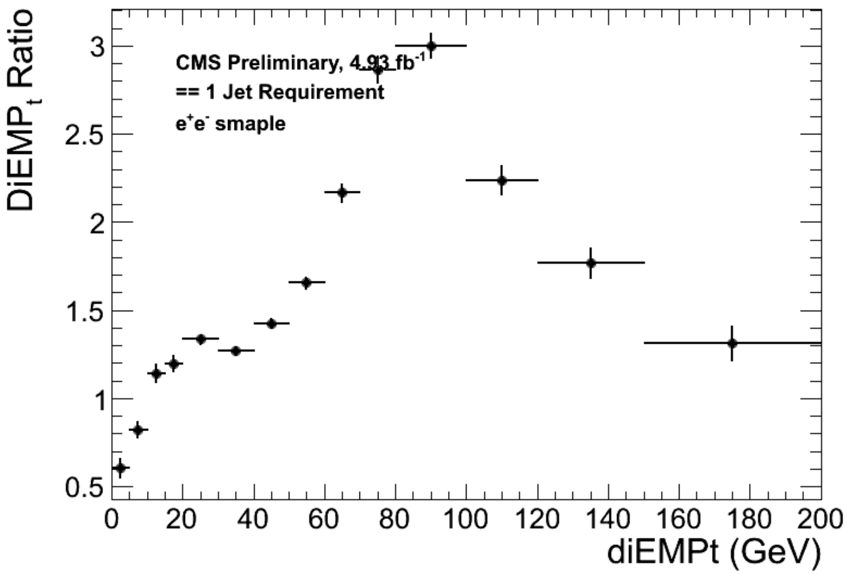
Estimation of QCD Background using ff sample

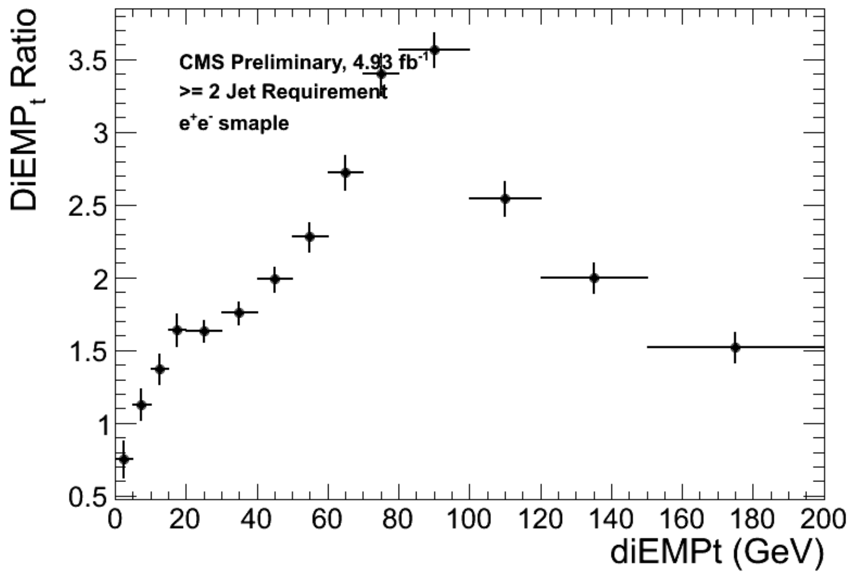






Estimation of QCD Background using ee sample



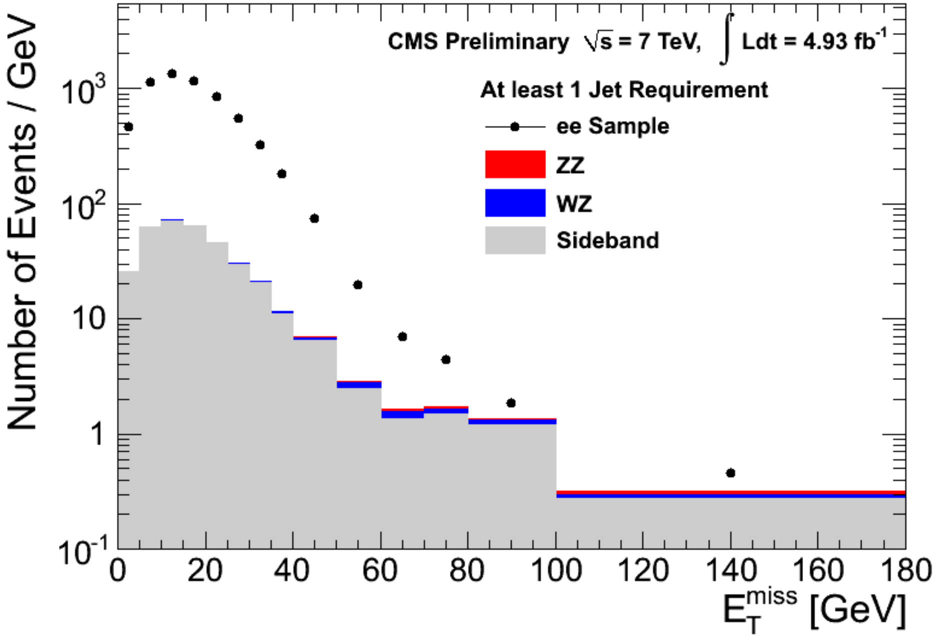


- Before we can use ee control sample to predict QCD MET distribution, we need to subtract other contributions with true MET contained in the sample.
- Use sideband method to subtract ttbar, WW contributions
- Use Monte Carlo samples to subtract Di-boson contributions center around Z invariant mass : WZ, ZZ processes

Estimation of QCD Background using ee sample

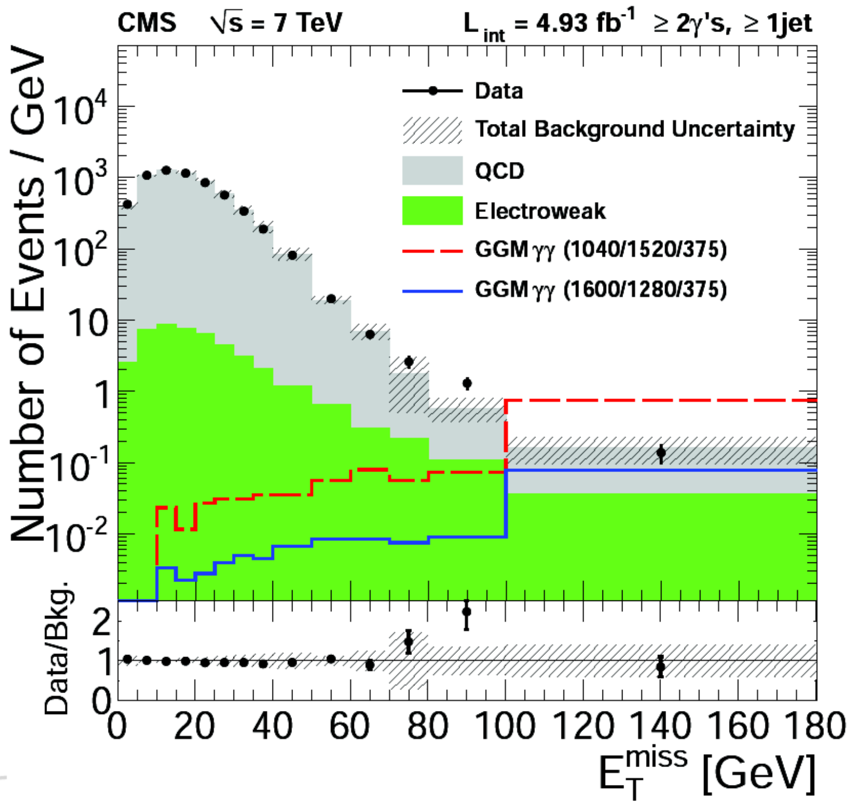
- Sideband subtraction method:
  - Signal region: invariant mass 81-101 GeV
  - Sidebands region: invariant mass 71-81 and 101-111 GeV
  - Also apply di-EMPt reweighting to ee sample in sideband regions
  - Subtract MET distribution of sideband regions from MET distribution of signal region

- Di-boson subtraction:
  - apply di-EMPt reweighting to MC samples
  - Normalize to total luminosity using NLO cross section and subtract MET distributions from MET distribution of ee sample



Result

E_T^{miss} bins [GeV]	50–60	60–70	70–80	80–100	> 100
QCD background	$183.8 \pm 17.7 \pm 12.5$	$67.3 \pm 10.7 \pm 13.6$	$15.4 \pm 5.1 \pm 11.5$	$9.4 \pm 4.0 \pm 0.7$	$10.1 \pm 4.2 \pm 1.4$
EWK background	$6.5 \pm 0.3 \pm 2.2$	$3.1 \pm 0.2 \pm 1.0$	$2.2 \pm 0.2 \pm 0.7$	$2.2 \pm 0.2 \pm 0.8$	$2.9 \pm 0.2 \pm 1.0$
Total background	$190.3 \pm 17.7 \pm 12.7$	$70.4 \pm 10.7 \pm 13.7$	$17.6 \pm 5.1 \pm 11.5$	$11.6 \pm 4.0 \pm 1.0$	$13.0 \pm 4.2 \pm 1.7$
Data	199	63	26	26	11



- Use ff sample as the main QCD prediction and take the difference between ff and ee samples as systematic error
- Good agreement between candidate MET distribution and background estimates

Systematic Uncertainties

Systematic	Uncertainty [%]
Integrated luminosity	4.5
Photon Data/MC scale	4
Jet energy scale	2
Renormalization scale	4 - 28
PDF error on cross section	4 - 66
PDF error on acceptance	0.1 - 9

Limit Setting Procedure

- Define likelihood ratio

$$Q = \frac{P(observation \mid signal + background\ hypothesis)}{P(observation \mid background\ hypothesis)}$$

$$CL_{sb} \equiv P_{sb}(Q \leq Q_{obs}) = \int_{-\infty}^{Q_{obs}} \frac{dP_{sb}}{dQ} dQ$$

$$CL_b \equiv P_b(Q \leq Q_{obs}) = \int_{-\infty}^{Q_{obs}} \frac{dP_b}{dQ} dQ$$

$$CL_s \equiv \frac{CL_{sb}}{CL_b}$$

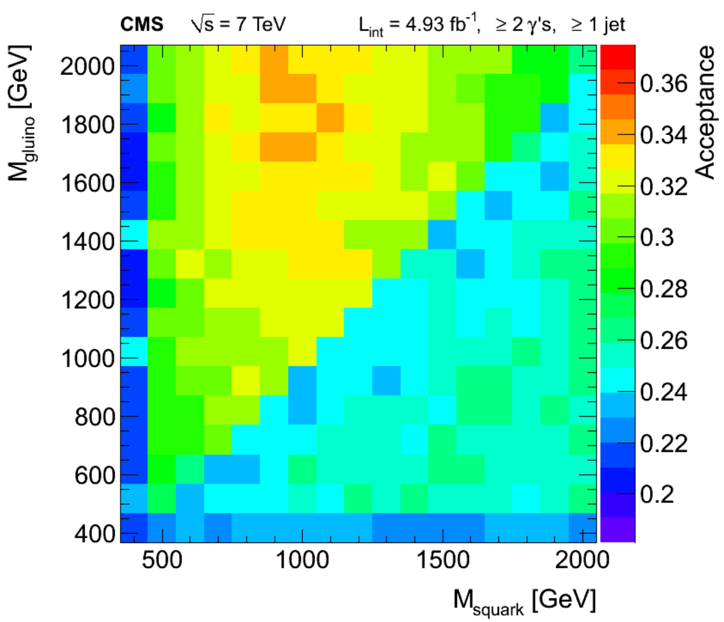
- CL_s is $\leq 5\%$ --> signal hypothesis is excluded at 95 % confidence level

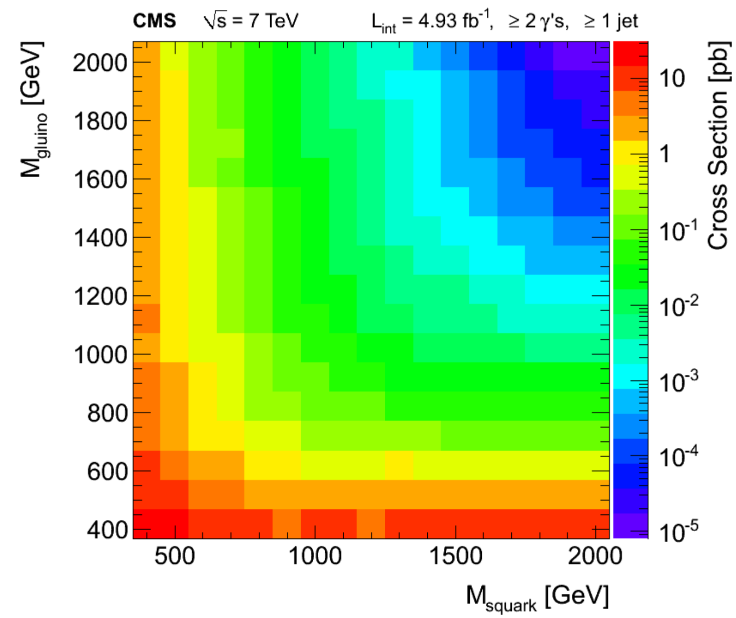
Interpretations

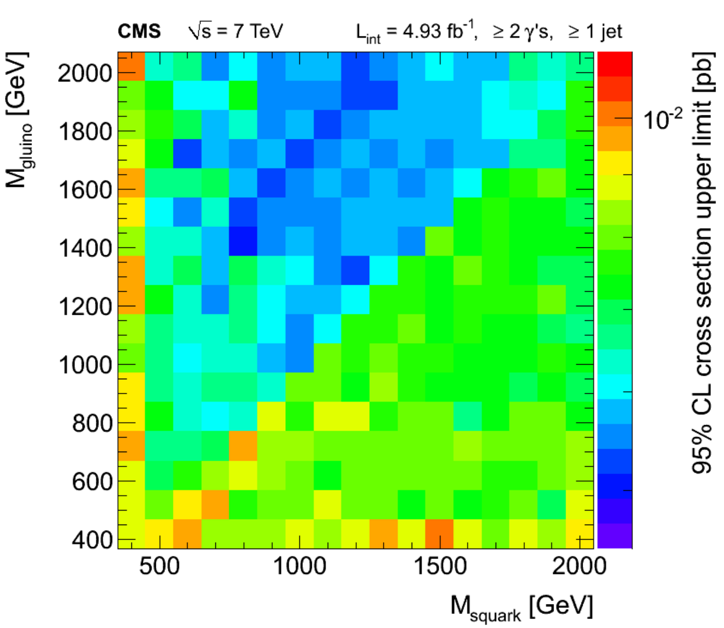
- Interpret results based on General Gauge Mediated model
- Choose planes in mass space and other SUSY particles are decoupled

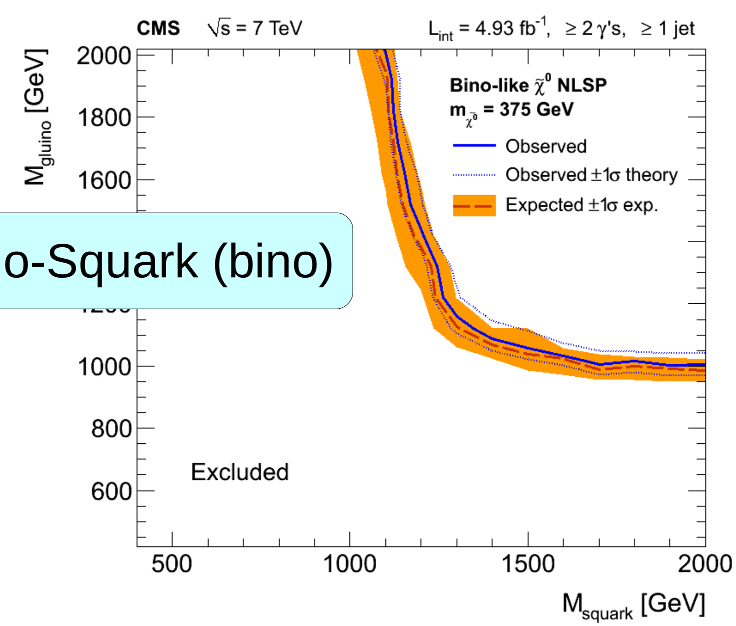
Scan	Gluino mass	Squark mass	Bino mass	Wino mass
Gluino-Squark (bino)	400-2000 GeV	400-2000 GeV	375 GeV	2000 GeV
Gluino-Squark (wino)	400-2000 GeV	400-2000 GeV	5000 GeV	375 GeV
Gluino-Bino	300-1500 GeV	5000 GeV	50-1500 GeV	2000 GeV
Gluino-Wino	300-1000 GeV	5000 GeV	5000 GeV	100-1000 GeV
Wino-Bino	5000 GeV	5000 GeV	50-1000 GeV	115-1000 GeV

Limit on Gluino-Squark (bino) Plane



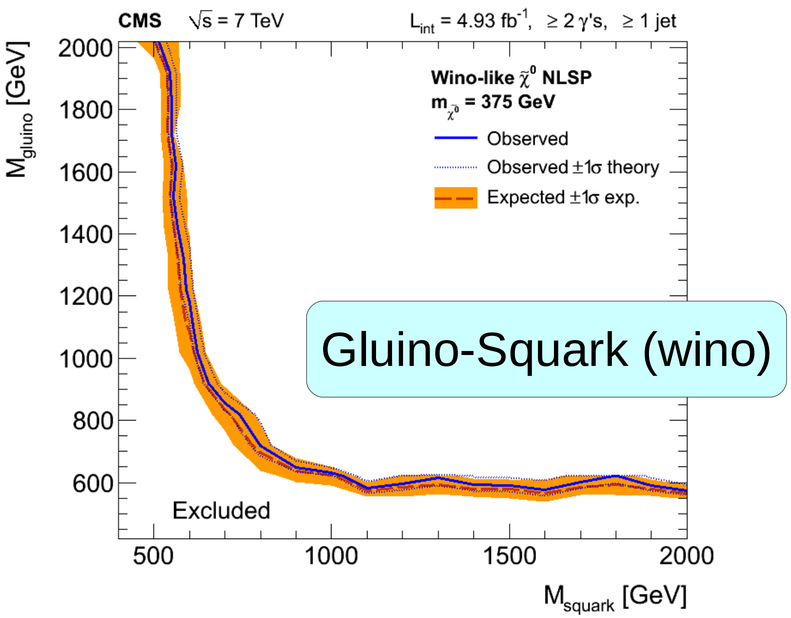


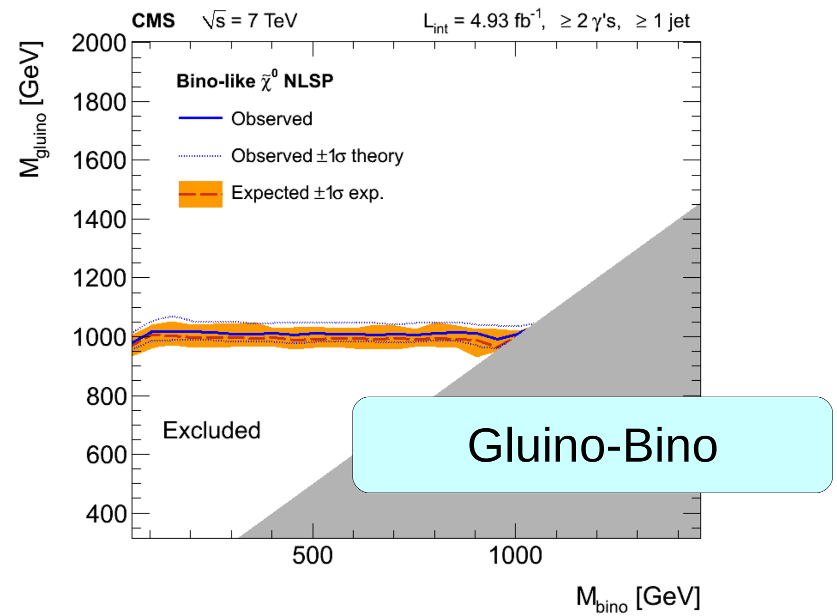


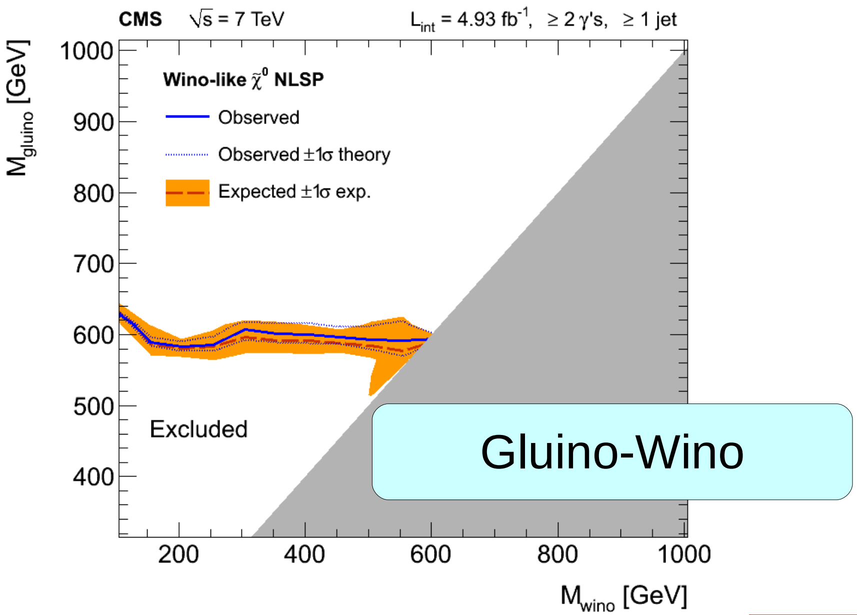


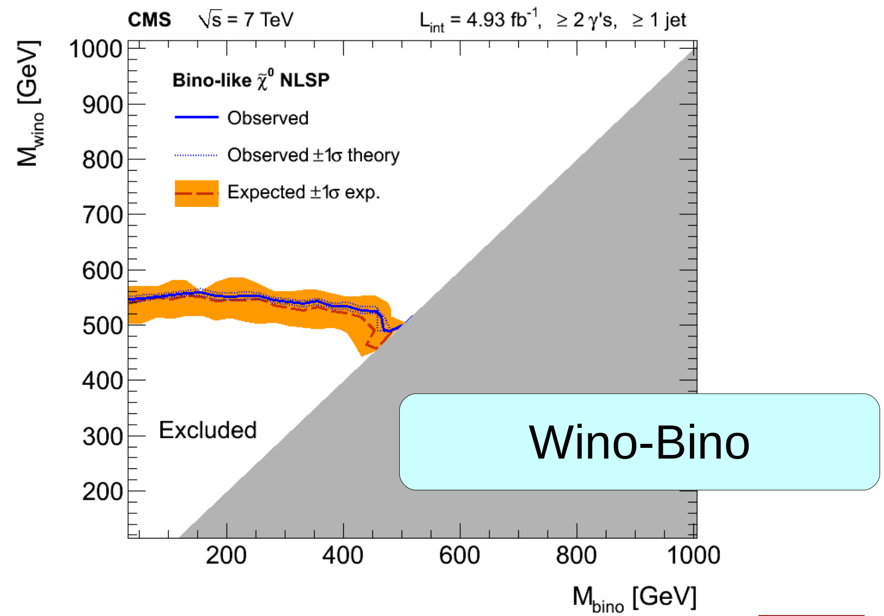
Gluino-Squark (bino)

Limits on Additional Planes in Phase Space

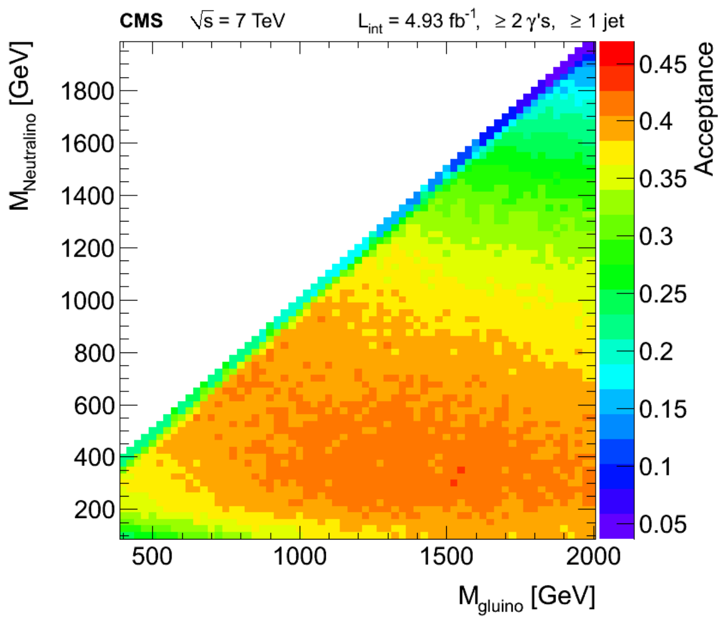


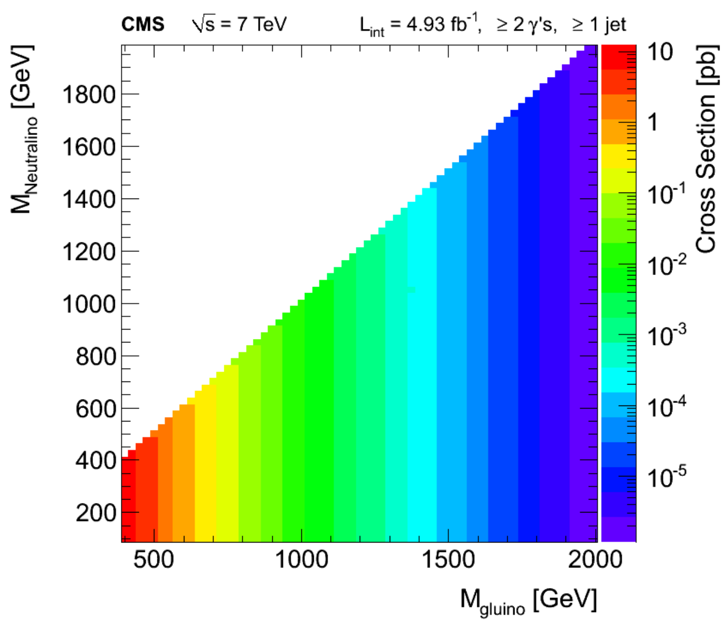


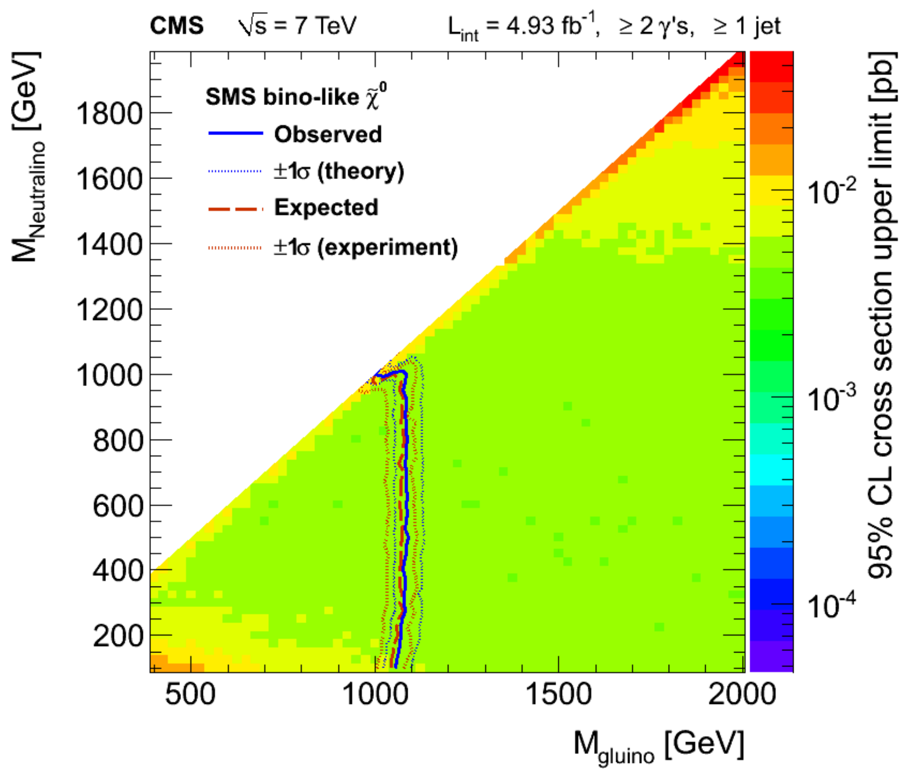




Simplified Model Interpretation



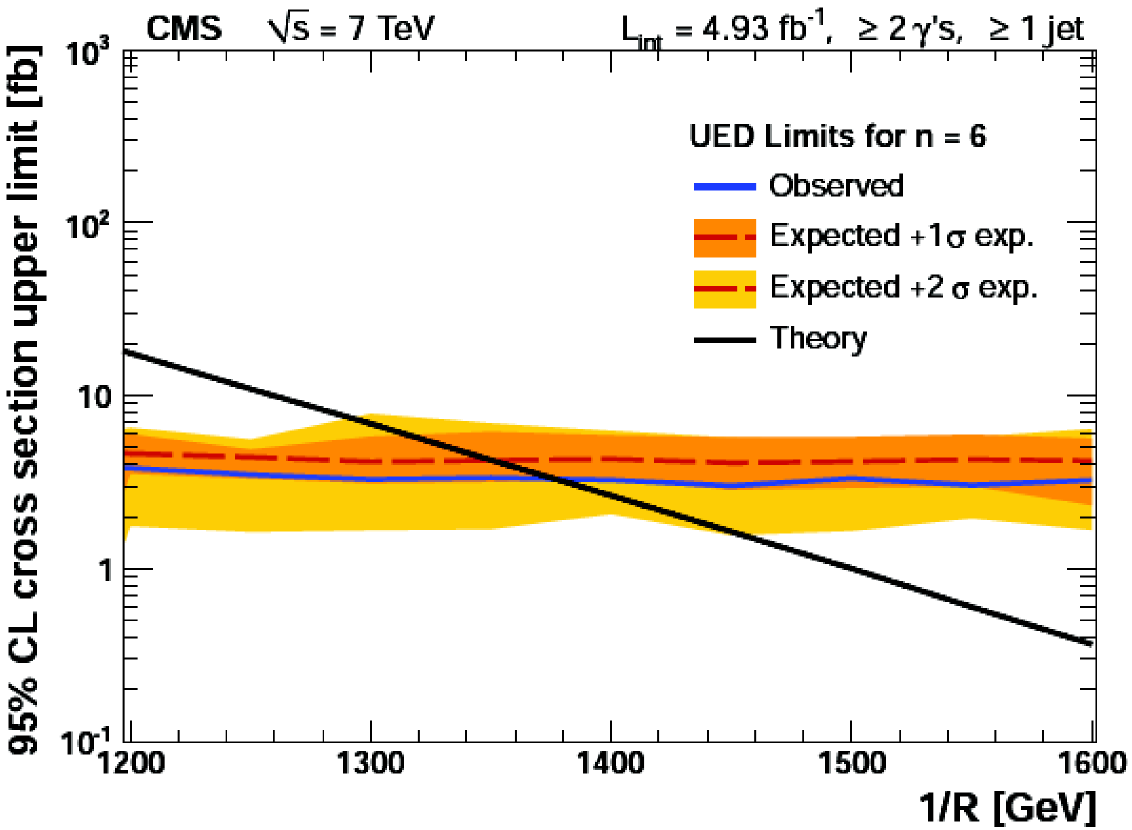




Interpretation on Universal Extra Dimensions

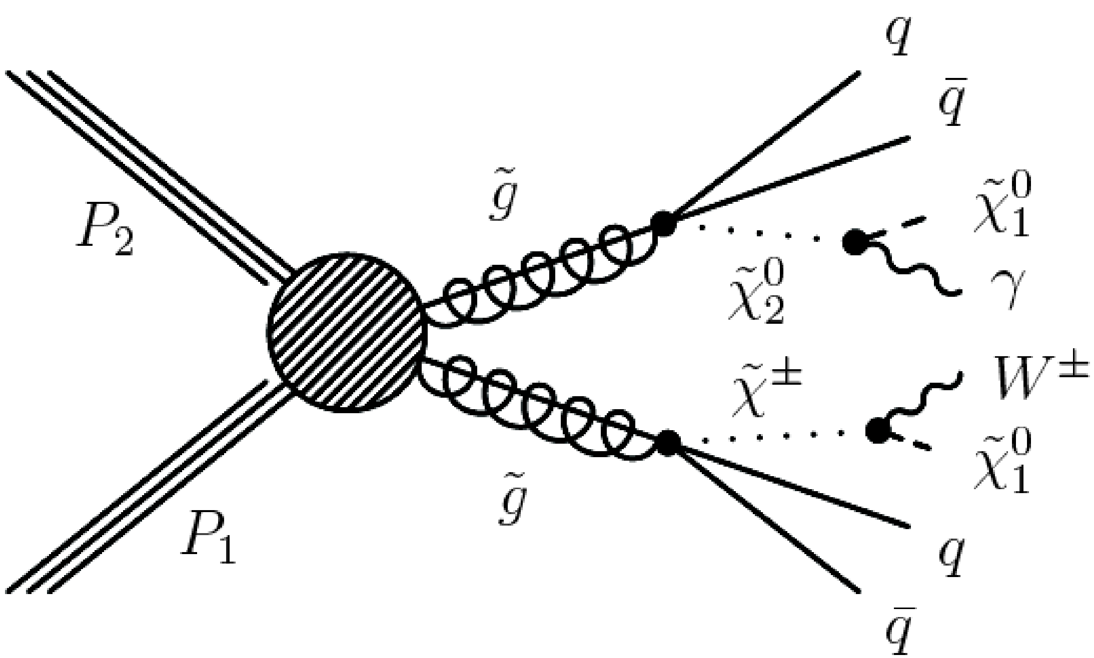
- SM particles can propagate in the additional dimensions --> production of a pair of Kaluza-Klein (KK) towers
- KK particles make cascade decay to lightest KK particle (LKP), which is the KK photon
- Assume the UED is embedded in a space of additional n Large Extra Dimensions where only gravitons propagate
- $\gamma^* \rightarrow \gamma + Graviton$
- KK photons decay gravitationally resulting Di-Photon + missing Et in the final state

Limit on UED



- n = 6, 1/R < 1380 GeV is excluded
- n = 2, 1/R < 1350 GeV is excluded
- Most strict UED limit to date

Search for Supersymmetry in Events with one Photon, Jets and Missing Transverse Energy



$W\gamma$ Simplified Model

Single Photon Analysis

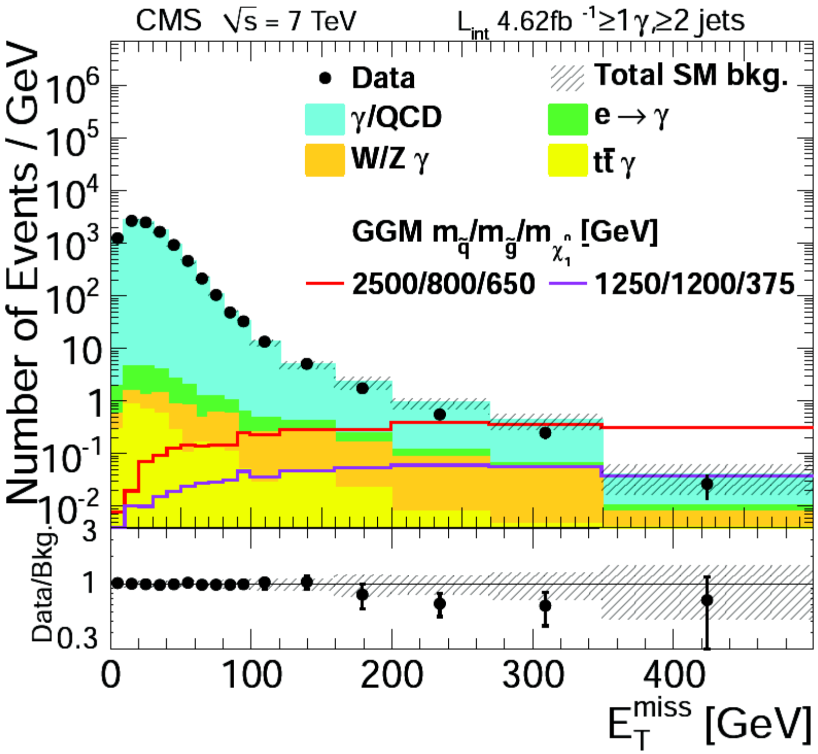
- Background:
  - QCD
  - Electroweak
  - $W/Z/t\bar{t}+\gamma$

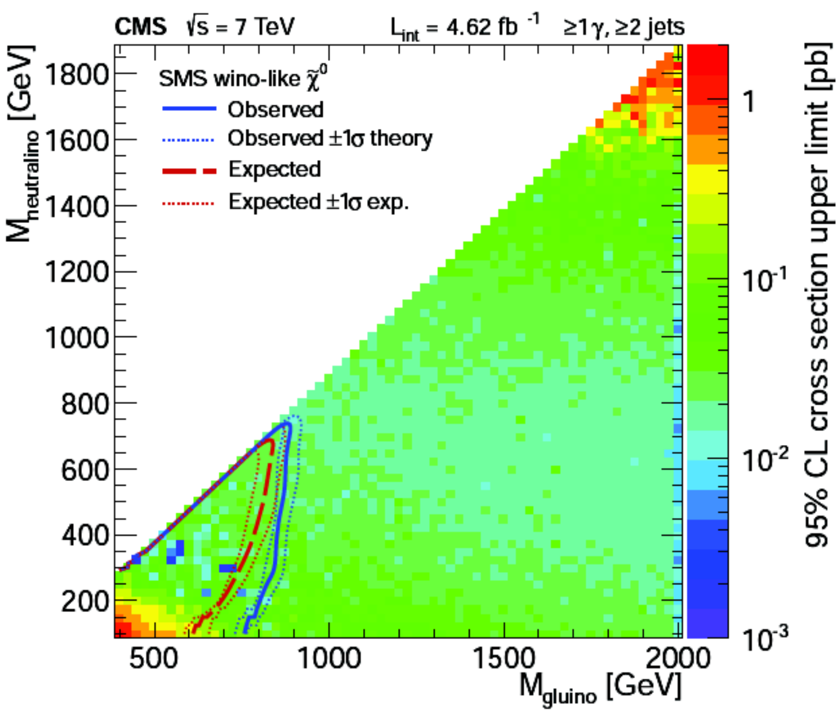
- Use Photon-HT trigger to catch signals
- Selections:
  - Photon Pt > 80 GeV
  - HT > 450 GeV
  - >= 2 Jets

- Analysis strategy and identification criteria are very similar to di-photon analysis
- weight the control sample from data (fake photon) to estimate QCD background
- Apply electron misidentification rate to the control sample from data (electron) to estimate electroweak background
- ISR/FSR $(W/Z/t\bar{t})$ contributions are determined directly from Monte Carlo samples

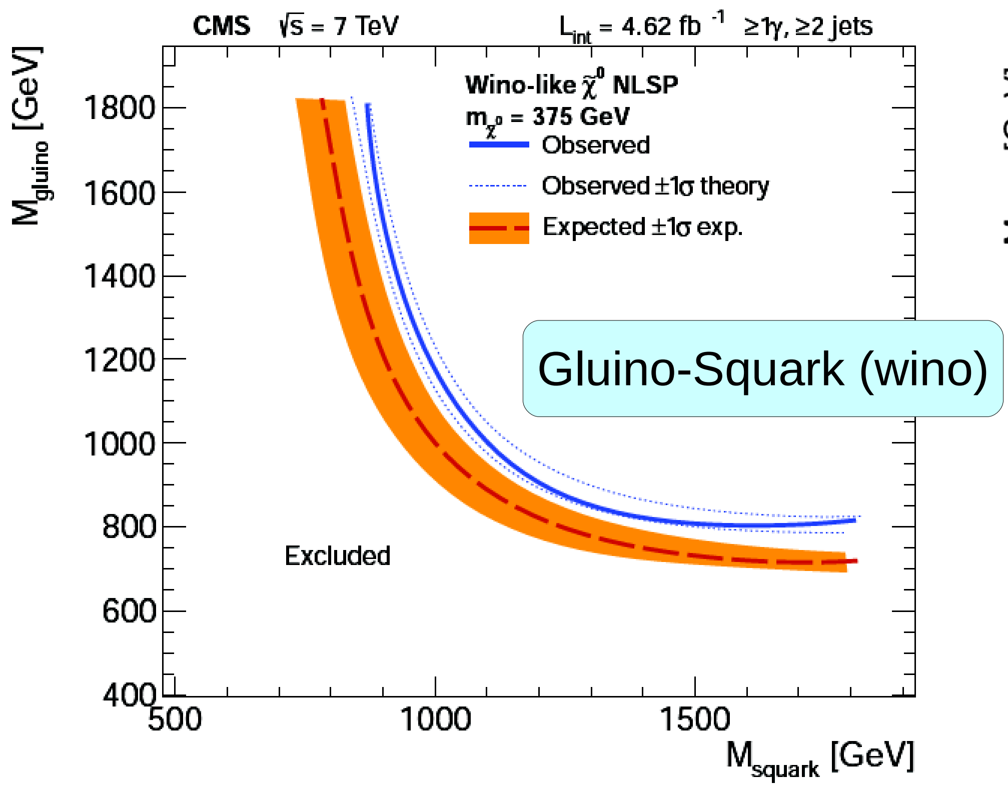
Results and Interpretation

E_T^{miss} bins [GeV]	100–120	120–160	160–200	200–270	270–350	> 350
QCD (from data)	262 ±37	173 ±27	82 ±24	55 ±14	29 ±11	6.8 ±4.2
$e \to \gamma$ (from data)	4.5 ±1.9	6.0 ±2.5	3.2 ±1.3	2.3 ±1.0	0.8 ±0.4	0.4 ±0.2
FSR/ISR (W,Z)	4.7 ±1.3	8.2 ±1.8	5.5 ±1.5	5.4 ±1.3	4.0 ±1.3	1.7 ±0.9
FSR/ISR ($t\bar{t}$)	0.6 ±0.3	1.7 ±0.6	0.9 ±0.4	0.5 ±0.4	0.4 ±0.3	≤ 0.01
Total SM estimation	272 ±37	189 ±27	91 ±24	63 ±14	34 ±11	8.8 ±4.3
Data	283	199	70	39	20	4

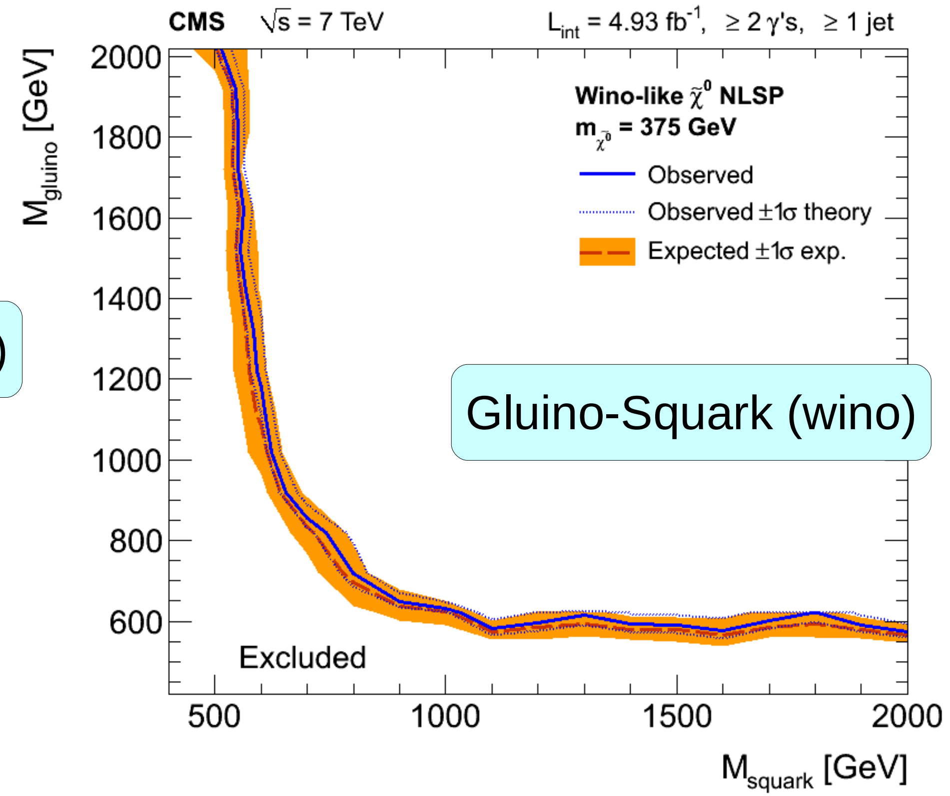




Limit on GGM Model



Single Photon Analysis



Di-Photon Analysis

- Single photon analysis improves CMS's sensitivity in wino-like case

Summary

- We have completed a search for GGM SUSY with di-photon final state using all of 2011 CMS data.
- Data-driven methods were used to estimate dominate backgrounds.
- We observe no excess beyond Standard Model.
- We set 95% CL upper limits on cross sections and exclude gluino and squark masses below

~1TeV (bino-like neutralino)

~600 GeV (wino-like neutralino)

~1 TeV (simplified model)

Backup Slides

Identification Details

- Photons :
  - In barrel region (|Eta| < 1.4442)
  - leading photon Et > 40 GeV, trailing photon Et > 25 GeV
  - combined Isolation (DR03 cone) < 6 GeV
  - H/E < 0.05
  - $\sigma_{i\eta i\eta} < 0.011$
  - No PixelSeed
  - r9 < 1.0

$$\sigma^2_{i\eta i\eta} = \frac{\sum_i^{5\times5} w_i(\eta_i - \bar{\eta}_{5\times5})^2}{\sum_i^{5\times5} w_i}, \quad w_i = max(0, 4.7 + ln\frac{E_i}{E_{5\times5}})$$

- Fake Photons:
  - Identical to photons but reverse combined Isolation (6 < Combined Isolation < 20 GeV) OR
  - $0.011 < \sigma_{i\eta i\eta} < 0.014$ (Combined Isolation < 20 GeV)

- Electrons :
  - Identical to photons but requiring PixelSeed

Identification and Event Selection Details

- Jets:
  - AK5 L1FastL2L3 corrected PFJet
  - Pt > 30 GeV/c
  - |Eta| < 2.6
  - Neutral Hadron Fraction < 0.99
  - Neutral EM Fraction < 0.99
  - Number of Constituents > 1
  - Charged Hadron Fraction > 0
  - Charged EM Fraction < 0.99
  - Charged Multiplicity > 0
  - dR between photons and jets >= 0.5 if require 1+jet
  - Jet cleaning cone size dR = 0.5

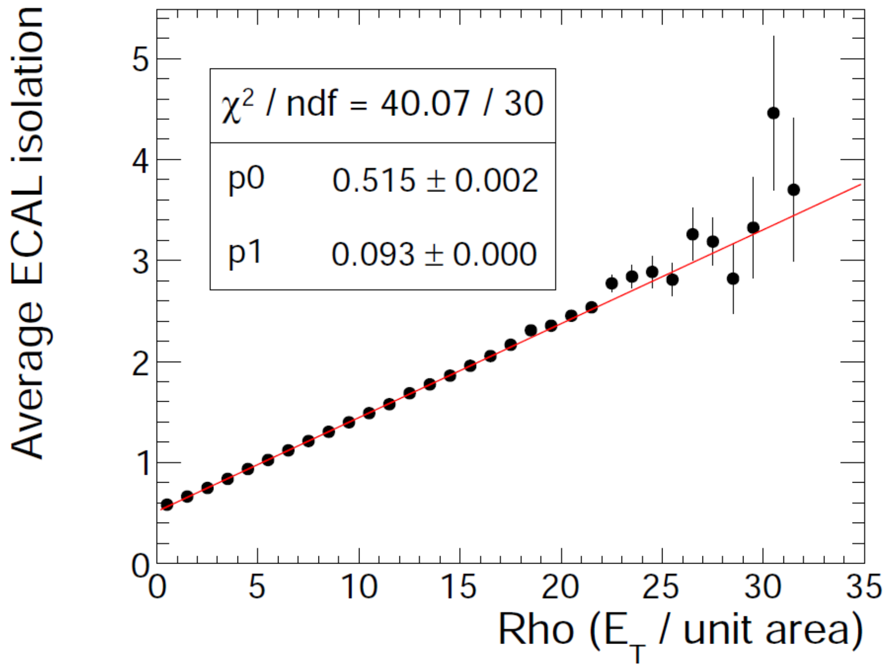
- Primary Vertex Selection:

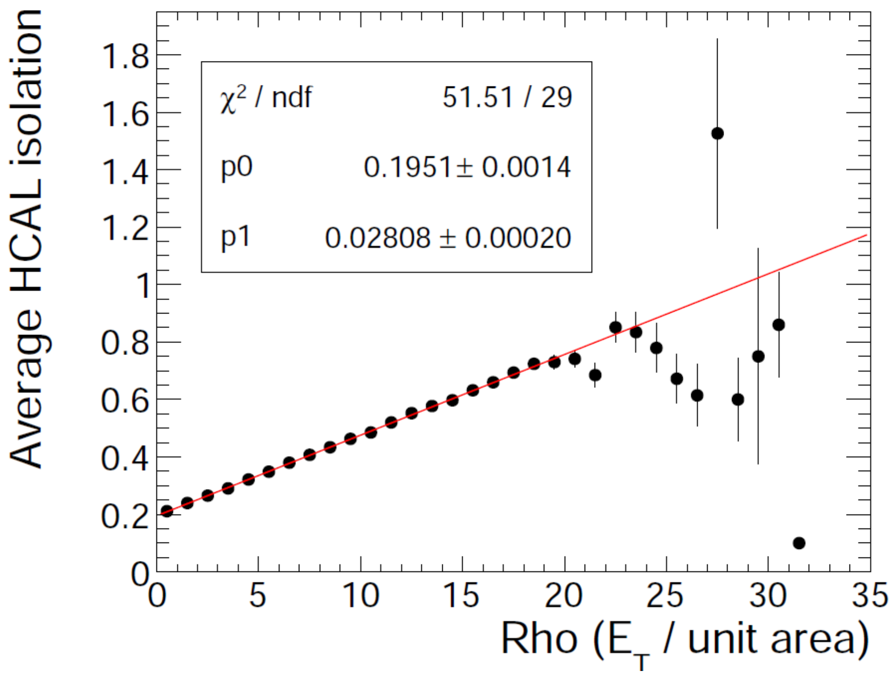
  Requiring at least one primary vertex
  - Not fake
  - Ndof > 4
  - fabs(z) < 24 cm
  - fabs(rho) < 2 cm

- Selected EM objects must be separated by dR > 0.6
- For no jet requirement case, dPhi between selected EM objects > 0.05
- Apply invariant mass 81- 101 GeV cut to ee sample

Pile-up Compensation

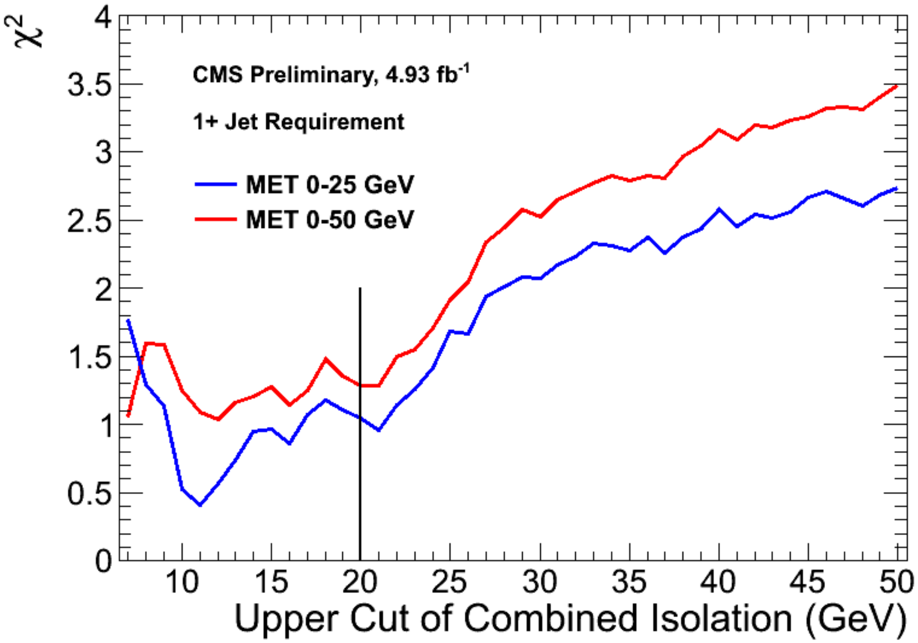
- $$Isolation_{ECAL,compensated} = Isolation_{ECAL} - \rho \times A_{ECAL,Eff}$$
- $$Isolation_{HCAL,compensated} = Isolation_{HCAL} - \rho \times A_{HCAL,Eff}$$
- ρ : average energy per unit area deposited in calorimeters for each event



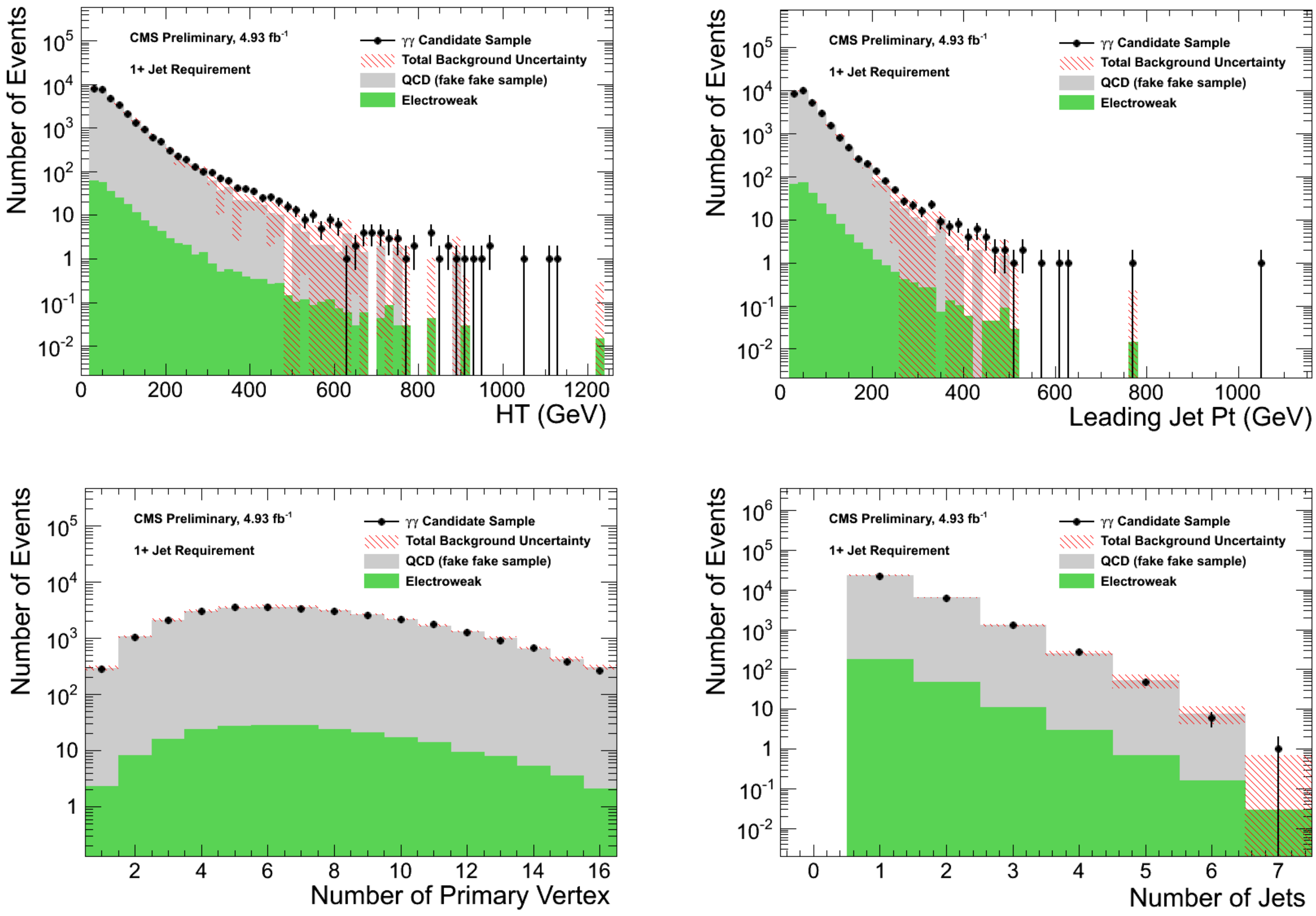


Optimization of Upper Isolation Cut

$$\chi^2 = \frac{1}{N_{\mathrm{bin}}} \sum_{i=1}^{N_{\mathrm{bin}}} \frac{(ff_i - \gamma\gamma_i)^2}{\sigma^2_{ff_i} + \sigma^2_{\gamma\gamma_i}}$$



Other Distributions



Di-Photon Analysis 8 TeV Results